High-energy cosmic gamma rays from the 'Single Source'

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Abstract

Some six years ago, we (Erlykin and Wolfendale, 1997) proposed the 'single source model' in which a local, recent supernova remnant (SNR) was responsible for the 'knee' in the cosmic ray (CR) energy spectrum at ~ 3 PeV. Stimulated by the paper by Bhadra (2002), which drew attention to a possible gamma ray signature of this local remnant, we now study the situation for the local source and we conclude that, in contrast to Bhadra's conclusion, the non-observation of this remnant is understandable - at least using our SNR model. It is due to the fact that this SNR, being local, develops in the local hot interstellar medium (HISM) with its low density of gas and also being nearby it will be an extended source occupying up to 40° of the sky and thus indistinguishable from the background.

1 Introduction

The 'knee', a rather sharp steepening in the primary cosmic ray (CR) energy spectrum at about 3 PeV, was inferred from the observation of a similar feature in the measured size spectrum of extensive air showers by Kulikov and Khristiansen (1958). The knee is commonly asserted to be due to an increasing failure of 'Galactic containment' of the CR generated by sources within the Galaxy, the containment being caused by the magnetic fields in the interstellar medium (ISM), However, it is the firmly-held view of the present authors that the knee is too sharp for this explanation and we have advanced what we claim to be a more realistic model. This is our 'single source (SS) model' (see Erlykin and Wolfendale, 1997, 2001b for recent details) which comprises cosmic ray acceleration up to the knee energy by supernova remnants, the knee itself being due to the truncation that occurs at 3 PeV for oxygen nuclei from a single, recent, nearby SNR. The other main accelerated nucleus at these energies is iron and its termination occurs at about 12 PeV where, it is claimed by us that there is a small second knee (when the spectrum is plotted as $E^3I(E)$ vs. E, the knees appear as small peaks). The remainder of the CR spectrum (at least to some 10^9 GeV, or so) is presumed due to 'super'-SNR and other sources and their spatial distribution is such as to give a comparatively smooth spectrum in the PeV region.

Erlykin and Wolfendale (to be referred to henceforth as EW) have examined a variety of other cosmic ray data and concluded that there is either support for the model or that the data are neutral. Very recently, low energy gamma ray data have also been studied (EW, 2002) and the well-known 'gamma ray excess' in the Inner Galaxy, and deficit in the Outer Galaxy, have been explained in terms of propagation differences dependent on the conditions in the ISM from which the gamma rays come. The results relate to Galaxy-wide properties and, although the SNR acceleration hypothesis has been invoked, there is no significant information about the single source.

It is at higher gamma ray energies where potential problems exist (e.g. Drury et al., 1994). Most recently, Bhadra (2002) has argued that the single source should be visible in TeV gamma rays, and it is not. This is the topic to be addressed here. We use the results found in a very recent paper (EW, 2003a to be referred to as I), where we made predictions of the fluxes and the angular distribution of gamma ray intensity from SNR of different ages and at different distances from the Sun. The threshold energies were taken as 0.1 GeV and 1 TeV.

A critical feature of the Bhadra estimate was the 'normalisation' of the SNR 'conditions' so as to give the CR energy density created by the single source at earth. We regard this as a legitimate procedure and we follow this path, although other features of our model differ considerably from those adopted by Bhadra. Our calculations are thus not simply a 're-run of the Bhadra calculations with different values for the parameters' but, rather, for what is certainly a more appropriate model of SNR acceleration and (less certainly, perhaps) a significantly different model of cosmic ray propagation.

2 The Bhadra estimate

Bhadra's model is rather straightforward, in principle, at least: particles are accelerated by the SNR shock to give a differential spectrum $AE^{-\gamma}$, with $\gamma = 2.0$, and these particles interact with the ambient (or swept-up) gas of density n, with $n = 1$ cm^{-3}. At this stage it is necessary to make critical remarks, however. Implicit in the Bhadra calculations is the assumption that the SNR shock accelerates the CR instantaneously, at '$t = 0$'. Although this can be used to give a viable mathematical model, such a situation is certainly not appropriate to a real SNR where the acceleration occurs over an extended period: $8 \cdot 10^4$ years in our model, and little different in other SNR acceleration models.

	Bhadra	EW
$E_{SN,CR}$ (10^{50} erg)	1.9	1.0
D (10^{29} cm^{2}s^{-1})	1.0	$2.25\,(E/10^3)^{0.5}$
n (cm^{-3})	1.0	3×10^{-3}
γ_p	2.0	2.15
$F_\gamma(> 0.1$ GeV) (cm^{-2}s^{-1})	2×10^{-7}	10^{-8}
$F_\gamma(> 1$ TeV) (cm^{-2}s^{-1})	4×10^{-11}	0.7×10^{-12}

Table 1: Values of the parameters adopted by Bhadra (2002) in comparison with those in the present work (denoted EW). The remnant is taken to be at 300 pc from the Sun. $E_{SN,CR}$ is the cosmic ray energy input from the SNR; D is the diffusion coefficient for normal, gaussian diffusion, E is in GeV; n is the density of the interstellar medium (ISM) in H-atoms cm^{-3}; γ_p is the exponent of the differential proton spectrum; $F_\gamma(> 0.1GeV)$ and $F_\gamma(> 1TeV)$ are the predicted gamma ray fluxes.

Nevertheless, we continue to describe the Bhadra calculations. It is assumed that the particles diffuse from the source a distance r from the Sun in a normal, Gaussian fashion with diffusion coefficient $D = 10^{29}$ cm^{2}s^{-1}. The parameters are chosen to give the required CR energy density at the Earth created by the single source. For instance, if the source is at the distance of 300 pc and it is 10^4 years old the total energy transferred from SN to CR is required to be $1.9{\cdot}10^{50}$ erg. The Table summarizes the most important parameters.

The expected minimum gamma ray flux above 0.1 GeV rises with the age of the SN from $0.2 \cdot 10^{-7}$cm^{-2}s^{-1} at 10^3 years to $2 \cdot 10^{-7}$cm^{-2}s^{-1} at 10^5 years and from $0.4 \cdot 10^{-11}$cm^{-2}s^{-1} to $4 \cdot 10^{-11}$cm^{-2}s^{-1} above 1 TeV, respectively. For the real candidates for the single source discussed in EW, (1997) (eg. Loop I, Clayton SNR) the expected fluxes are substantially higher. Comparing these fluxes with the diffuse gamma ray background Bhadra found that for the present gamma ray telescopes it should have been possible to observe the single source. Since there has been no claim for an observation Bhadra concluded that the single source cannot be such a SNR.

Turning to our remarks on the validity of Bhadra's model, in addition to the basic problem with the assumption about the instantaneous acceleration there are two further reasons why we cannot allow this conclusion to stand and, in fact, Bhadra made the neeeded reservations, viz. '*the detection could be crucial, depending on the angular size of the object*' and '*unless the source is in a lower density environment*'. These are the points addressed in the following sections. We require, first, the likely whereabouts of the single source such that it can give the particle spectrum needed in the knee region.

3 The present treatment

3.1 The predicted particle spectrum

We have calculated cosmic ray energy spectra originating from SNR of different ages and distances. The model of acceleration was described in EW (2001a) and briefly in I. The propagation of accelerated cosmic rays through the ISM was calculated using two alternative assumptions about the mode of propagation from the source: 'anomalous' diffusion, viz. making allowance for the fractal-like nature of the ISM, and normal, Gaussian, diffusion. Following the work of Lagutin et al.(2001a,b) we distinguish these two modes by a parameter α determined by the fractal nature of the medium; α is equal to 1 or 2 for anomalous or normal diffusion, respectively.

The difference between the two modes can be seen most clearly in the shape of the lateral distribution function for the cosmic ray intensity: $\frac{1}{(1+x^2)^2}$ for $\alpha = 1$ and $exp(-\frac{x^2}{4})$ for $\alpha = 2$, with $x = \frac{r}{R_d}$, r being the distance from the radius $R_s = 100$ pc where the particles start to diffuse and R_d being the diffusion radius which is defined as $R_d = H_z(\frac{t}{\tau(E)})^{\frac{1}{\alpha}}$, i.e., there is a different time dependence for the two modes. $H_z = 1$ kpc for the vertical scale of the galactic halo and t and $\tau(E)$ are the diffusion time and time against escape, respectively, for the protons. Details of the propagation model are given in EW (2002) and in I.

The difference in the two lateral distributions is quite dramatic. Thus, for $x = 2$, 4, 6 and 8, the ratio of the intensity for anomalous diffusion to that for normal diffusion changes as 0.11, 0.19, 5.9 and $2.1{\cdot}10^3$, respectively. The long tail for anomalous diffusion - the occasional considerable 'penetration' ('Levy flights') - can have important implications. An example is that for the secondary to primary ratio; to our knowledge the implications have not been worked out.

We have determined the proton energy spectra expected for the two values of α and these are given in Figures 1 and 2. Also indicated in the Figures is the spectrum 'required' by the SS model. We have argued that the 'needed' particles are oxygen nuclei for the first 'peak' at 3 PeV and iron nuclei for the second 'peak' at $\sim$ 12 PeV, and the requirement has been converted to rigidity before plotting, in Figures 1 and 2. An alternative association of the 'peaks' with helium and oxygen changes the indicated SS spectrum no more than by 17%. (EW, 2003b).

Dotted lines above and below the 'SS' curve indicate its uncertainty limits; the least uncertainty and therefore the most important constraint of the SS model is in the knee region. The limits come from the fit to the experimental data on the primary energy spectrum measured by means of the Cherenkov light emitted by extensive air showers (EW, 2001b). These data determine the magnitude of the uncertainty in the range of about a decade below the knee. At lower energies, - $10^3 - 10^4$ GeV - the upper limit is determined by the uncertainty of the direct measurements of the primary CR energy spectrum (Biermann and Wiebel-Sooth, 1999). Although the shape of the SS spectrum has been adopted from the theoretical model of Berezhko et al.(1996) its lower experimental limit at low energies is completely uncertain because the contribution of the Single Source to the total CR intensity at these energies is negligibly small and even consistent with zero. However, the actual value of the uncertainty at TeV energies is not important for this analysis because we have made a quantitative comparison of the calculated proton spectra with the SS spectrum only in the most important range of energies, viz. that covering a decade below the knee. The energy range of $logE = 4.6 - 5.6$ used for this comparison is indicated in the Figures by *'min'* and *'max'*.

Some comments are needed about the Figures. It is evident that $\alpha = 2$ always gives a bad fit (Figure 2) whereas $\alpha = 1$ can give a reasonable one, at least for energies above 10^4 GeV, up to the cut-off at $4{\cdot}10^5$ GeV, for a range of age (T) and distance (R) values [1]. Calculations made for a wide range of T and R allow us to estimate the range over which there is satisfactory agreement between calculations and the SS model; it is $85 < T < 115$ kyear and $250 < R < 400$ pc for the adopted set of input parameters.

It is relevant to point out that larger distances, too, would give a good fit to the spectral *shape*. The necessary upward movement in intensity could be effected by increasing the fraction of the shock energy going into CR. As was pointed out in I, Berezhko et al.,(1996) used much bigger values than the 10% used here - their highest being 80%. Specifically, for 100 kyear an increase in CR yield by a factor 8 would allow the source to be at ~ 650 pc.

The shape and the absolute intensity of the CR energy spectrum give the most stringent constraints on the age and distance. The T-R region of SNR which could give an acceptable spectrum (for our standard '10%') is shown in Figure 3 by the 95% confidence level contour. Following Bhadra's approach we have also used such an integrated characteristic of the spectrum as the energy density contained in it. Again, we used for the comparison just the last decade of the spectrum below the knee, because intensities at low energies are so poorly determined by the Single Source Model. The energy density contained in the spectrum of our single source between $4 \cdot 10^4$ GeV and $4 \cdot 10^5$ GeV is $1.84{\cdot}10^{-4}$eVcm^{-3}. Comparison of this value, allowing for uncertainty, with those expected for SNR of different ages and distances gives an acceptable T-R region indicated by the dashed line in Figure 3. It overlaps with the region deduced from the comparison of the spectral shapes. This proves the consistency of these results, although we must admit that the two methods are not completely independent, because consistent values for the spectra should inevitably give consistent energy densities contained in them.

In any case this analysis indicates that our single source should be located at about 300 - 350 pc from the Sun and should be about 90 - 100 kyears old. We know of no objection to such parameters (see §4 for its likely location).

3.2 The predicted gamma ray flux

3.2.1 Calculations for the standard gas density

Fluxes of gamma rays from SNR of different ages and at different distances from the Sun have been calculated in I. In Figure 3 we show contours of the fluxes calculated for the interactions

[1] In spite of the fact that such an integral characteristic as χ^2/ndf has a formally acceptable value for $\alpha = 2$ at T$\approx$ 85 kyear the slopes of the proton spectra are too steep to give the sharp knee and we do not consider it as a good contender.

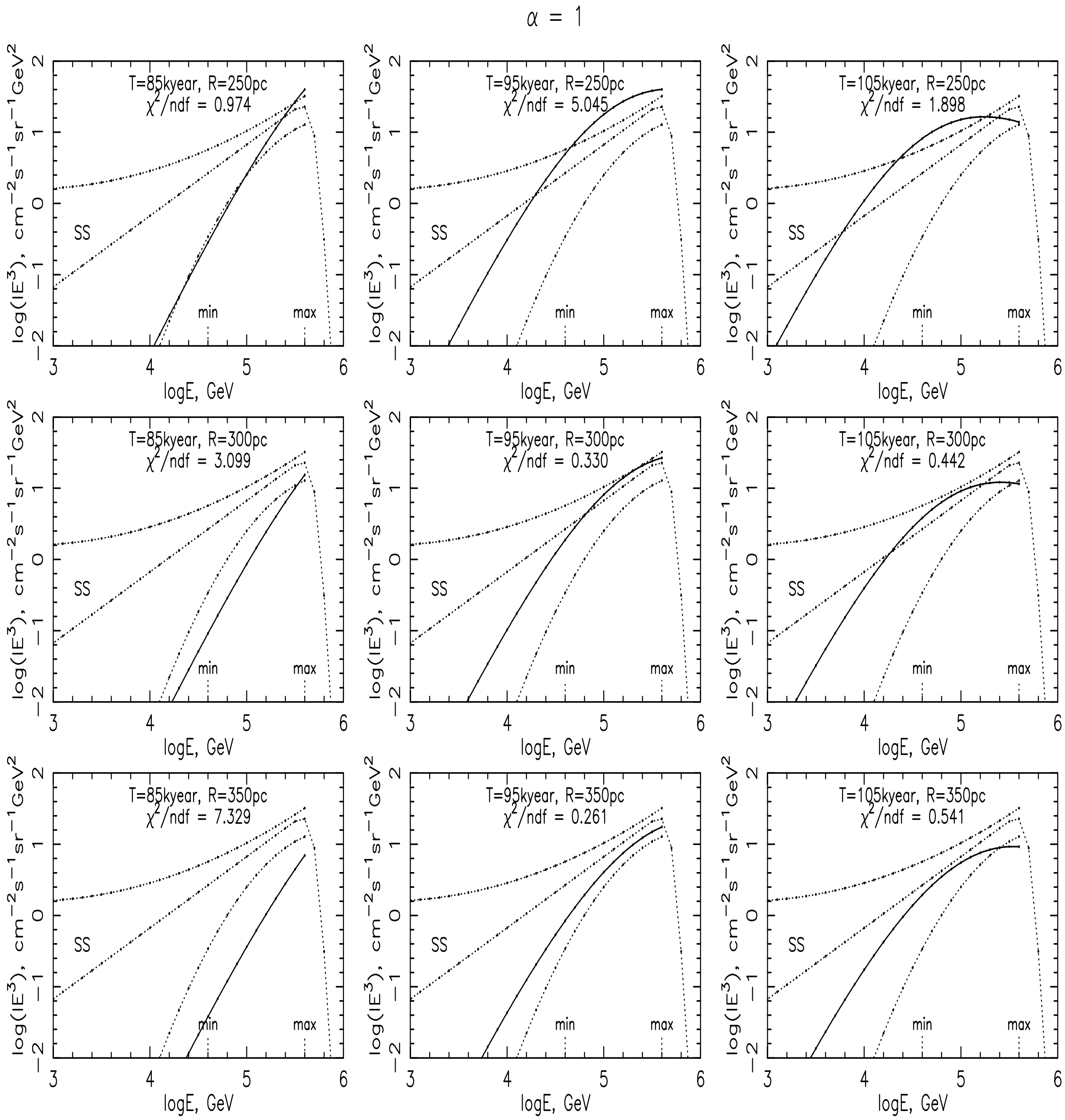

Figure 1: Energy spectra of protons (full lines) expected from SNR of different ages (T) and at different distances (R) from the Sun, as indicated inside the graphs, compared with the rigidity spectrum of CR according to our Single Source Model (dotted line denoted by SS). Dotted lines above and below the SS line indicate its uncertainty limits. SNR protons propagate through the ISM by means of anomalous diffusion with $\alpha = 1$ (EW, 2002) (rigidity and energy are, of course, the same for protons). The energy interval used for the comparison of proton spectra with the SS model is marked by *min* and *max*. The result of the comparison in terms of the reduced χ^2, i.e. χ^2 divided by the number of degrees of freedom, χ^2/ndf, is shown inside the Figures.

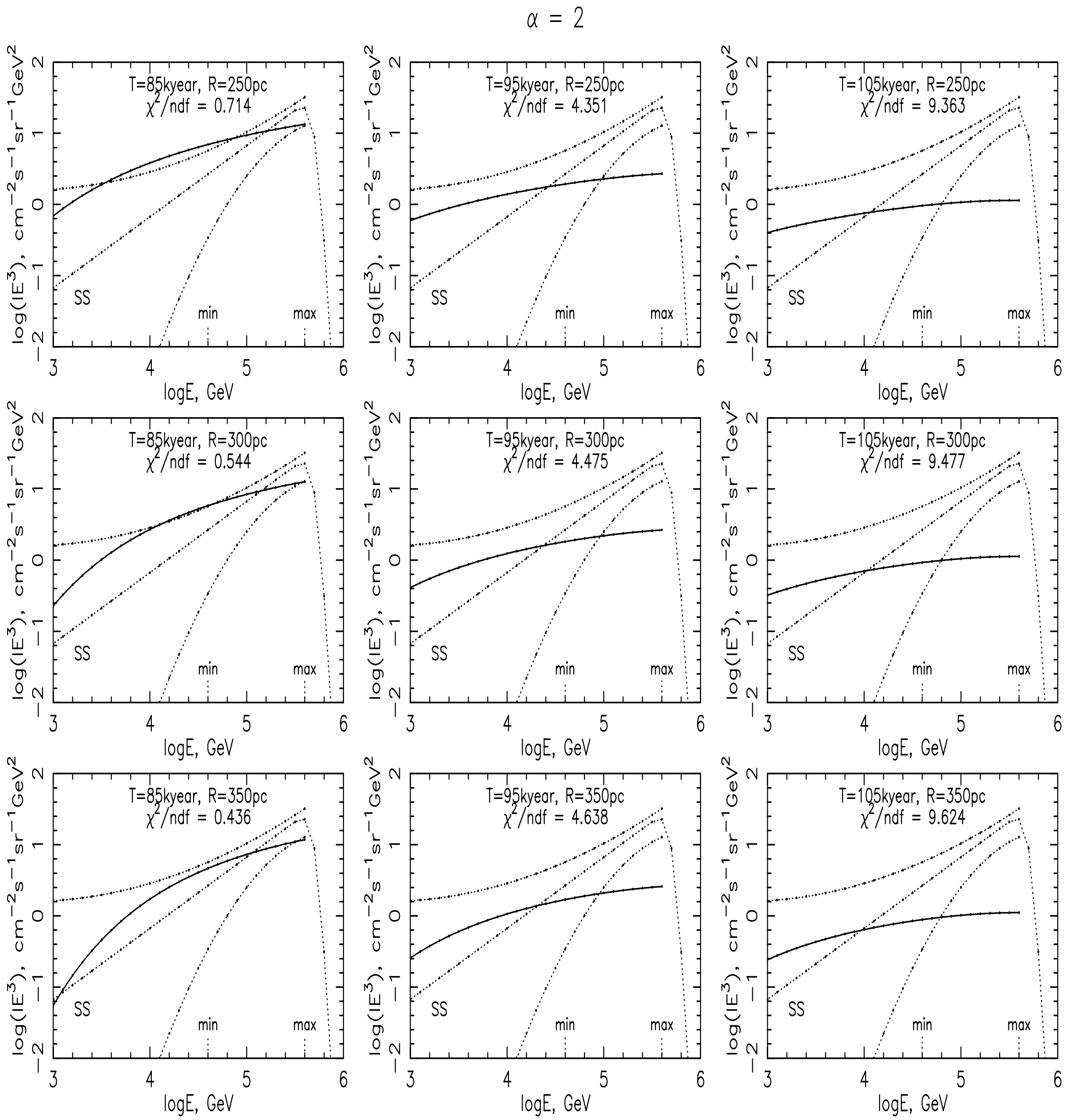

Figure 2: The same as in Figure 1, but for normal diffusion with $\alpha = 2$.

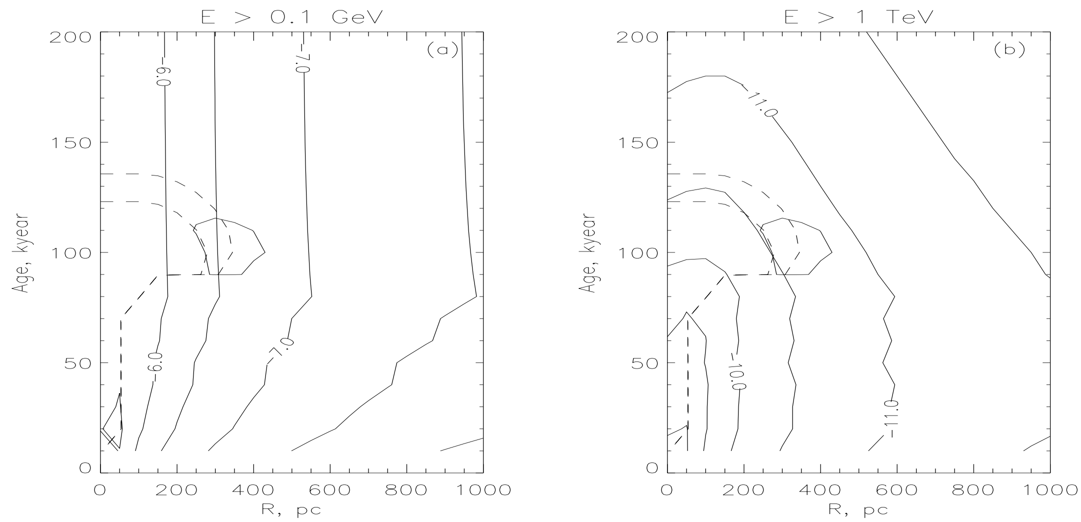

Figure 3: Age - Distance diagram for a SNR which is responsible for the formation of the knee - i.e. for our 'Single Source'. The inserted full-line contour in the center indicates the 95% confidence level region deduced from the analysis of the shape and the intensity of the CR particle spectra; the dashed lines show limits based on the comparison of the energy density contained in the Single Source. Full-line contours show the expected total gamma ray fluxes with the energy of gamma quanta above 0.1 GeV (a) and 1 TeV (b) expected for PP-interactions. Labels on the contours indicate values of log(Flux), the flux being in units of $cm^{-2}s^{-1}$.

of protons, accelerated by the SNR, which propagate through the ISM by way of anomalous diffusion ($\alpha = 1$) and collide with nuclei of the ISM, The density of the ISM for these calculations has been taken to be our standard $n = 1cm^{-3}$. It is seen that the expected fluxes are about $3{\cdot}10^{-7}cm^{-2}s^{-1}$ for $E_\gamma > 0.1$ GeV and about $2{\cdot}10^{-11}cm^{-2}s^{-1}$ for $E_\gamma > 1$ TeV.

It is necessary now to study the implications of the fact that the cosmic rays from our Single Sourse are not only protons, but that the composition is mixed. At the same rigidity it consists of 21% P, 48% O, 13% 'heavy' nuclei ($10 < Z < 23$) and 18% Fe. Because nuclei of the same rigidity are more efficient in the production of gamma quanta (see I), the expected fluxes should be increased by a factor of 10.5. This gives expected fluxes of $\sim 3 \cdot 10^{-6}cm^{-2}s^{-1}$ for $E_\gamma > 0.1$ GeV and $\sim 2 \cdot 10^{-10}cm^{-2}s^{-1}$ for $E_\gamma > 1$ TeV. It is necessary to point out that the CR energy injection is higher by the same amount.

3.2.2 The appropriate gas density to adopt

Since this is a first order effect, a detailed examination of the problem is required. As pointed out in I, there are several aspects that need attention, specifically:
(i) the effect of the pre-SNR winds from the progenitor star in excavating a 'hole' into which the SNR shock expands, this is essentially the origin of the HISM (note that for vey young SNR, however, the progenitor star's wind may have *enhanced* the density);

(ii) the general ISM density in the region where the progenitor star was situated and
(iii) the pressure, or otherwise, of clumpy gas (often molecular) in the vicinity of the SNR.

In the present case, it is almost certain that the progenitor star - at 300-350 pc from the sun - was in the Hot Interstellar Medium, where the density is often quoted as $n \simeq 3 \cdot 10^{-3}$ cm^{-3} (Berezhko et al., 1996; Cox and Reynolds, 1987, for example quote a density of $4 \cdot 10^{-3}$cm^{-3}). Indeed, since all our model calculations assume this to be the case, a low density target material is a prerequisite. The assumption of the HISM comes from two factors:
(i) the absolute maximum particle energy needed to explain the knee ($3 \cdot 10^6$ GeV for oxygen nuclei) appears only for this density, in the Berezhko et al. model, and
(ii) the HISM is eminently reasonable for a nearby source.

Factor (ii) can be examined in more detail. Insofar as the sun is located on the edge of a spiral arm, in one hemisphere (the South), at least, the gas density will be low. Frish (1997) has considered the situation in detail. Beyond the very local region, where there is the 'Local Fluff' (of extent ~3 pc) in certain directions the column density of atomic (and molecular) hydrogen is very low. The 'Local Bubble' (Loop I) is quickly reached, this Bubble being caused by several SN over the past Myear. Here, one expects the HISM, with its density $\sim 3 \cdot 10^{-3}$ cm^{-3}. Concerning the interarm region, Frish quotes an undisturbed part as having a density of $4 \cdot 10^{-4}$ cm^{-3}, i.e. even smaller. However, much of the Local Bubble is here and the density will be higher because of material brought in from elsewhere.

Interestingly, Frish (1981) suggested, earlier, that the sun is embedded in one of the superbubble shells associated with the formation of the Scorpius-Centaurus Association. Another possibility for the formation of Loop I ('but very similar to that given above is that it was caused by activity in the 'Upper Centaurus Lupus' subgroup some 14-15 Myear ago (De Geus, 1991)).

A distinction must be made between a 'recent' SN exploding in Loop I, i.e. in the low density HISM caused by previous SNR and stellar activity, and the low level gamma ray flux from Loop I as a whole. This latter was considered in I and it was argued there that the mean density overall, allowing for molecular clouds inside the Loop, and the piled-up gas in the edges of the Loop, is $\langle n \rangle \simeq 0.1$ cm^{-3}. There is no conflict with our $n = 3 \cdot 10^{-3}$ cm^{-3} if the single source is well into the interior.

3.2.3 The predicted gamma ray flux

With $n = 3 \cdot 10^{-3}$, the predicted flux is reduced to $\sim 10^{-8}$ cm^{-2}s^{-1} for E_γ >0.1 GeV and $\sim 0.7 \cdot 10^{-12}$cm^{-2}s^{-1} for $E_\gamma > 1$ TeV.

If, surprisingly, the source is not in the HISM in the Local Bubble, but is isolated, then as was discussed in I, $n \sim 0.1$cm^{-3} and the predicted fluxes are $\sim 3 \cdot 10^{-7}$cm^{-2}s^{-1} for $E_\gamma > 0.1$ GeV and $\sim 2 \cdot 10^{-11}$cm^{-2}s^{-1} for $E_\gamma > 1$ TeV.

The predicted fluxes are shown in Figure 4, for the various possibilities of n and Z.

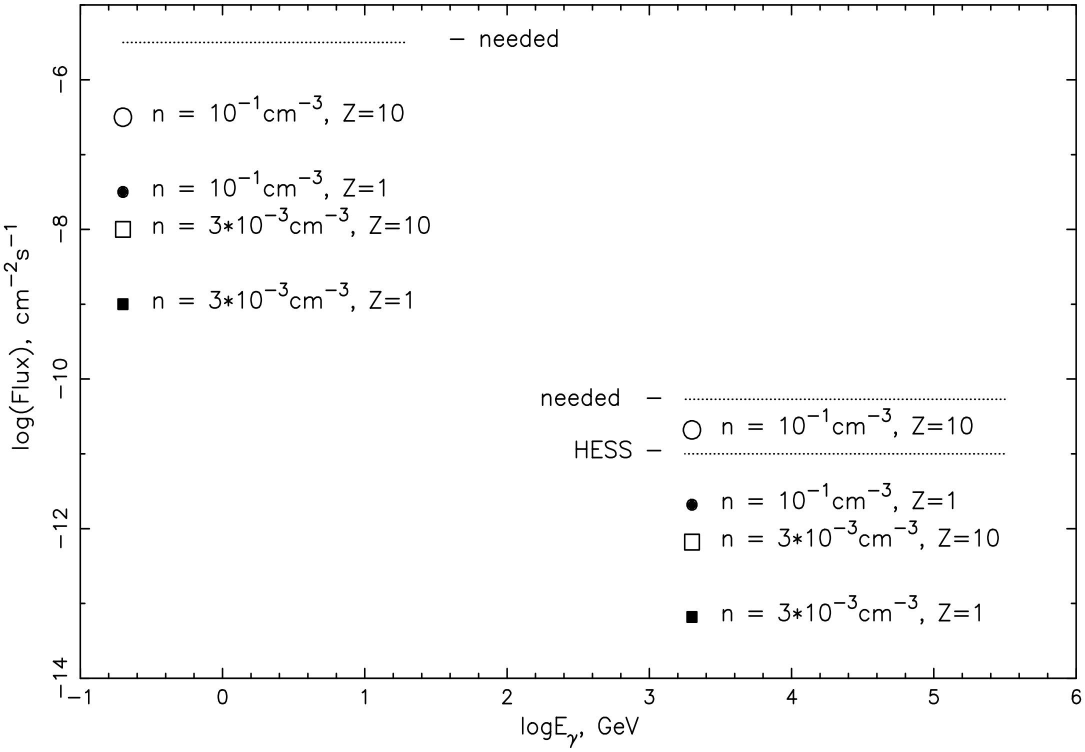

Figure 4: Schematic representation of the gamma ray fluxes from the claimed 'Single Source' at energies $E_\gamma > 0.1$ GeV and > 1 TeV for a variety of scenarios. The source would be at $\sim 300-350$ pc from us and have an age of $\sim 90-100$ kyear, i.e. it would be only 10-20 kyear since the particles were released by the remnant. The dotted lines marked 'needed' are the minimum fluxes required for the source to have been detected by the arrays in use up to now. As an indication of the future we also give the estimated minimum detectable flux for $E_\gamma > 1$ TeV for a source of 20° radius, from the work of Aharonian et al.,(1997). These authors give results for 1000 hours of observation of a 'point' source and one of 1° extent; our estimate arises from an extrapolation, based on results described in I. The work reported relates to the then proposed IACT (100 GeV - class imaging atmospheric telescope array), denoted 'HESS'.

3.3 The limiting sensitivity in practice

The sources must be detected against a background due to the Galactic diffuse emission arising from CR - ISM nucleus interactions (and, in the case of TeV gamma rays, protons interacting in the atmosphere). This background can be allowed for in a straightforward manner for 'point' sources, where a subtraction can be made of the signal nearby to the source, but for extended sources the problem is much more severe. The angular radius of a SNR, which is 90-100 kyear old, seen from a distance of 300-350 pc is about 20° (see also Figure 5 in I). For such a large size the determination of the background by a linear interpolation of the intensity between the adjacent regions is not at all accurate. Estimates of the background based on the known column density of the target gas, although more appropriate, are again not sufficiently accurate because the intensity of the initiating cosmic rays along the line of sight cannot be assumed to be strictly constant.

Estimates of the limiting fluxes were made from the available data and they are given in

I. For a source of radius 20° the average limits are $3 \cdot 10^{-6}\text{cm}^{-2}\text{s}^{-1}$ for $E_\gamma > 0.1$ GeV and $5 \cdot 10^{-11}\text{cm}^{-2}\text{s}^{-1}$ for $E_\gamma > 1$ TeV. These limiting sensitivities, which relate to observations made so far, are indicated in Figure 4.

The lower energy limit comes from an extrapolation of the EGRET results (Hartman et al, 1999), which refer to small angular sizes, to 20°. That for the upper energy band comes largely from the Tibet and HEGRA arrays (Amenomori et al., 2001 and Lampeitl et al., 2001, respectively).

It is instructive to examine these sensitivities in terms of the background fluxes. For $E_\gamma > 0.1$ GeV, the intensity at low latitudes towards the Galactic Anticenter is about $10^{-4}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ and for our 20°-radius source ($\Omega = 0.4$ sr) the flux would be $4 \cdot 10^{-5}\text{cm}^{-2}\text{s}^{-1}$. The plotted limit of $3 \cdot 10^{-6}\text{cm}^{-2}\text{s}^{-1}$ is thus 8% of the background. For the direction to the Galactic Center, where the background is higher by a factor of 3, this percentage is reduced to (2-3)%. When allowance is made for other sources of uncertainty our adopted limit seems reasonable.

For $E_\gamma > 1$ TeV, the corresponding background in the Galactic Anticenter direction has been estimated to be $\sim 1.6 \cdot 10^{-9}\text{cm}^{-2}\text{s}^{-1}$ (Porter and Protheroe, 1999), viz a flux of $(6-7) \cdot 10^{-10}\text{cm}^{-2}\text{s}^{-1}$ over a 20°-radius source. Our adopted limit of $5 \cdot 10^{-11}\text{cm}^{-2}\text{s}^{-1}$ is thus the same: ∼8% of the background. In the direction of the Galactic Center the background is expected to be twice as large and the fraction of the limiting flux falls to ∼4%. This figure, too, is reasonable in view of misidentified proton contributions and a variety of technical problems associated with making absolute measurements at different zenith angles.

4 Conclusions

The conclusions are indicated in Figure 4. Only if the single source is in a 'high' density region ($n \sim 0.1$ cm^{-3}) and the primaries are 'heavy' nuclei (Z = 10) (with consequent high CR energy injection) will it be possible to detect the Single Source at high energies. Such a situation is not impossible but there would be problems for our Single Source model with such a high ambient density, specifically that it would not be possible with the model in use to reach the required 3 PeV energy at the knee. Insofar as we consider it very likely that the source is in the HISM and is extended, the chance of detecting it with contemporary instruments is considered, by us, to be very low. There are, however, hopes for the future. It is germane to consider in which direction future, improved, gamma ray detectors should be pointed in order to see it. The best that can be done here is to suggest the general direction of Loop I. However, since this structure occupies about 25% of the sky the 'advice' is not very helpful.

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